

MARS RESOURCES

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ABSTRACT

The most important resources of Mars for the early exploration phase will be oxygen and water, derived from the martian atmosphere and regolith, which will be used for propellant and life support. Rocks and soil may be used in unprocessed form as shielding materials for habitats, or in minimally processed form to expand habitable living and work space. Resources necessary to conduct manufacturing and agricultural projects are potentially available, but will await advanced stages of Mars habitation before they are utilized.

INTRODUCTION

In the foreseeable future, the transportation cost of sending people or material to Mars will be high. Thus, for even the first manned missions to Mars, an effort should be made to utilize the indigenous materials of the planet, and any sustained presence must be supported by utilization of Martian resources.

Mars resembles the Earth enough in its geological history and current state that one can imagine the availability of practically anything that can be found on Earth, in terms of inorganic mineral resources (Cordell, 1984). Its biotic history is uncertain, certainly much less extensive than the Earth and perhaps totally absent, so concentration of elements and compounds by biogenic means is not expected. It has polar ice caps and a thin atmosphere. Surface alteration processes due to the interaction of atmosphere and surface are expected. These are the potential sources of useful products. Solar energy flux is approximately one quarter that of the Earth; geothermal heat may be tappable in some places, but early missions will probably carry nuclear energy supplies.

With adequate supplies of energy, it is probable that any substance available on Earth can be obtained from the materials of Mars. However, this paper focuses on our current state of knowledge of Mars resources and their potential early uses.

IMPORTANT EARLY USES OF MARS RESOURCES

The earliest uses of Mars resources will come where: 1) the product is required in substantial quantities and would otherwise be transported from Earth; 2) the mass of product desired is significantly larger than the mass of the equipment which must be transported to Mars to produce it; 3) the raw materials are readily available; and 4) the energy necessary for manufacturing the product is available. By-products of primary processes may find uses that do not meet these criteria. Among uses which may fit this category are: 1) extraction of propellant (H_2 , O_2 , CO , CH_4 , etc.) for Mars-Earth space transportation and trans-Mars transportation; 2) shielding of habitats and equipment from radiation, and insulation of structures for thermal control; 3) expansion of living and work space; 4) makeup of consumables in life support systems and expansion of controlled life support systems.

PROPELLANT

Propellant produced at Mars or on its moons could greatly reduce Mars-orbit and Mars-Earth transportation (see Ref. this volume). In the past, proposals have been made to extract CO and O_2 for propellants from abundant CO_2 in the atmosphere. This is a predictable and accessible resource. Liquid hydrogen and oxygen also could be prepared from water, which exists as ice in polar regions and probably as permafrost elsewhere. Propellants could also be produced from carbonaceous-chondrite-like material, which probably exists on Phobos and Deimos.

SHIELDING AND INSULATION

The radiation environment at the surface of Mars is sufficiently harsh that long term habitation requires substantial shielding, by up to the equivalent of 3 meters of rock or mineral material. Surface temperatures at equatorial latitudes are approximately $240^{\circ}K$ in daytime and $190^{\circ}K$ at night. Loose soil or rock can probably be used for thermal insulation of habitats; however, for specific applications, it may be necessary to develop better insulators than those obtainable from the unprocessed rock and soil materials.

EXPANSION OF LIVING AND WORK SPACE

The first visitors to Mars will be severely cramped in their living and working space. Extended staytimes will be much easier if ways are available to expand the pressurizable volume that can be occupied for the crew. Because of the need for shielding, these expansions must be subsurface structures. Thus, there will be a requirement for structural materials that can support the necessary loads. This requirement could be met with non-metallic materials (fused or sintered silicates, or concretes) or metals. Seals for enclosures and interconnections to the outside environment will require materials from Earth at first, but local production will undoubtedly receive significant attention because these structures will control the rate of habitat expansion.

LIFE SUPPORT SYSTEM REQUIREMENTS

An abundant supply of water is essential for many aspects of life support systems, for direct use by humans, for agriculture, and for manufacturing. A large reservoir of water must be available to a permanent base. Oxygen and nitrogen are principal components of the atmosphere in which humans can exist, and CO_2 is the principal constituent of botanical interest. To the extent that closed ecological life support systems can be established, the resupply requirement for these compounds can be reduced; however, some irretrievable losses or at least sinks with very long residence times will be present, and in order to expand the initial base replenishment of these elements and compounds will be necessary from indigenous sources. It would be useful also to have sources of the principal nutrients for plants, although life support system closure can reduce the need for these materials.

MARS MATERIAL RESOURCE AVAILABILITY

The principal potential sources of materials on Mars can be categorized into four general groups: 1) atmosphere; 2) ground ice (permafrost, polar caps); 3) primary (igneous) rocks; and 4) regolith (dust and altered igneous rock) and sedimentary deposits formed by redistribution of the regolith. The moons of Mars represent another distinct category of material with potential resource implications.

ATMOSPHERE

The atmosphere of Mars consists of CO_2 (95.3%), N_2 (2.7%), Ar (1.6%), O_2 (0.1%), CO (0.1%), and small amounts of water and noble gases (Owen et al, 1977). Total surface atmospheric pressures measured by Viking are in the range of 7-8 millibars (Hess et al, 1977). A seasonal reduction is correlated with precipitation of CO_2 at the South pole and the pressure rises as CO_2 is sublimated. Peak surface temperatures at the Viking sites were 240°K and lowest temperatures were slightly less than 190°K .

The amount of water in the atmosphere is small, on the order of 100 precipitable microns (Farmer, et al, 1977). The entire atmosphere contains approximately the equivalent of 1.3km^3 of ice.

From time to time, the Martian atmosphere develops dust storms, which raise substantial quantities of what must be very fine dust which can remain aloft for weeks at a time. Most dust storms begin in the southern hemisphere when the planet is near perihelion and is receiving maximum solar energy. The dust is carried northward and longitudinally, but the continual supply of dust suggests that much of the material is eventually returned to the southern hemisphere. The Hellas basin, a large low area in the southern hemisphere, may be a sink for much of the dust, and possibly a source for new dust storms (Mutch et al, 1976).

ICE IN THE SUBSURFACE AND POLAR CAPS

Mars' atmosphere has small amounts of water vapor. A perennial ice layer of a few meters thickness has been inferred at both poles, extending to about 10 degrees equatorward. This overlays a series of layered deposits that apparently consist of a mixture of dust and ice. The total thickness is perhaps 1-2 km in the south and 4-6 km in the north, with perhaps 85 percent of the material consisting of ice. In the south, there is a seasonal cap of dry ice.

Morphological evidence (canyons, channels) strongly suggest the former presence of liquid water. In order to explain the quantities of water that would be required, a reservoir other than the polar caps must have existed in the past and may exist now. This is generally believed to be permafrost, and morphological observations have been used to infer its

distribution (Squyres, 1985). Chaotic terrain, overlapped lobate deposits of crater ejecta, and patterned ground all have been interpreted in terms of the former presence of water. Creep deformation of ice in a matrix of silicate deposits, similar to rock glaciers on Earth, has been cited by Squyres and Carr (1984) as evidence for the current presence of ground ice. The regions of high ice content may extend to depths of 1 km or more, which would make ground ice the largest water reservoir on the planet.

The creep features indicative of ground ice are notably absent between 30 degrees north and south on the planet, suggesting that the regolith has outgassed in equatorial regions.

IGNEOUS ROCKS

Mars currently exhibits the largest volcanic landforms of the solar system. These features are inferred to be basaltic from their morphology. Features such as Olympus Mons are believed to be relatively young, based on the distribution of impact craters, and may have been highly active until a billion years ago. In all other terrestrial planets studied intensively to date (Earth, Moon, Venus), basaltic volcanism is a consistent feature (Basaltic Volcanism Study Project, 1981). Earlier internal igneous activity may have been basaltic or possibly more primitive (ultrabasic, komatiitic), but in any case can be inferred to be extensive.

Few direct data exist on the compositions of Martian volcanic rocks. Analysis of the Viking X-ray fluorescence experiment data indicated that the surface fine material, dominated by weathering products, was derived primarily from mafic (basaltic ?) material, low in trace elements, alkalis and aluminum (Toulmin et al, 1977).

Recently, strong evidence has accumulated that the Shergottite meteorites (and perhaps the Nakhilites and Chassignite) are of Martian derivation (Bogard and Nyquist, 1983). Among other evidence, the presence of trapped noble gases similar to those measured by Viking in the Martian atmosphere and different from all other terrestrial or meteoritic noble gas patterns is compelling. The crystallization age of the shergottites

is on the order of one billion years, approximately the inferred age of the large volcanic landforms. The meteorites were probably expelled from Mars by one or more impact events that introduced substantial shock damage.

Minerals in the shergottites are principally the silicates olivine, iron-calcium-magnesium pyroxenes (augite and pigeonite), intermediate plagioclase feldspar (sodium-calcium aluminosilicate), and small amounts of silica, with titanomagnetite (titanium-bearing iron oxide), with up to 1 percent of a calcium phosphate mineral, whitlockite, and minor amounts of iron sulfides. This composition is consistent with inferences from the Viking analyses. No primary mineral containing water of crystallization (e.g. amphibole, mica) has been observed. However, these rocks are more highly oxidized than any other differentiated (igneous) meteorites.

If shergottite-like basalt is common on Mars, other rock compositions may have also developed locally. In slow-cooling (subsurface) environments, separation of olivine, pyroxene and feldspar could have led to significant enrichments in silica, alkalis and alumina to form granitic or rhyolitic rocks. Where volcanic materials came into contact with ice, a variety of unique rock types may have formed, some of which may have produced hydrothermal deposits. Cordell (1985) has speculated that Mars may have as diverse a set of igneous and hydrothermal deposits as the Earth. Although speculative, these represent targets to be sought in further exploration of the planet.

REGOLITH AND SEDIMENTARY MATERIAL

The principal means of rock degradation on Mars appears to be impact cratering. Locally, comminution through the action of fluids has certainly occurred, as the material eroded from the major canyons attests. Chemical weathering is probably a minor source of physical degradation of primary rock. At both Viking landing sites, abundant fine-grained materials are present, and the occurrence of dust storms indicates the existence of substantial quantities of ultrafine material.

Following physical degradation, chemical weathering may have been effective in changing the chemical composition of the particles. Viking

inorganic analyses are consistent with a soil composition containing aluminum-poor iron-rich clay minerals and iron oxides, plus sulfates, carbonates, and chlorides developed by leaching and precipitation of water-soluble phases by liquid water or possibly by thin films of moisture (Toulmin et al, 1977). Surface reflection spectra are dominated by Fe^{3+} + $-\text{O}^{2-}$ absorption bands, but are more consistent with spectra expected from altered volcanic glass than from specific clay minerals (Singer, 1982). If the original rock composition was similar to that of the shergottites, one might expect the soil to contain minor amounts of free silica, unreacted feldspar, and phosphate. It is of interest that soils present in the dry valleys of Antarctica, where liquid water is generally absent, are similarly enriched in chlorine, sulfate and carbonate (Gibson et al, 1983), suggesting concentration mechanisms for these elements by soil capillary action.

PHOBOS AND DEIMOS

Phobos and Deimos were imaged by the Viking orbiters. Phobos was shown to have complex surface features and both bodies are saturated with respect to impact craters greater than 300m (Veverka and Duxbury, 1977). Both bodies are spectrally uniformly gray and both have low mean density (Duxbury et al, 1979). For these reasons, it has been speculated that they are similar in composition to carbonaceous chondrites, a class of meteorites (asteroids) rich in clay minerals (hydrated silicates) and organic compounds (Pollack et al, 1973).

TYPICAL RESOURCE EXTRACTION PROCESSES

Table 1 gives estimates of the mass, power and productivity of extraction of some useful resources from Martian and Phobos/Deimos materials. In general, these processes will include mining (or concentration from the atmosphere), separation of beneficial minerals, chemical reactors, and storage. No subsequent processing is described here.

TABLE 1
TYPICAL CHARACTERISTICS OF MATERIAL PROCESSING SYSTEMS

PROCESS	FEEDSTOCK	PLANT MASS (KG)	PLANT POWER (KW) *	PRODUCT	REFERENCE
CO ₂ Extraction from Atmos- phere	Atmos.	250	6	1000 KG/day	Ash (1978) Frisbee (1983)
Electrolysis of CO ₂ to O ₂ +CO	1000 KG CO ₂ /Day	1000	10	750 KG O ₂ /D. 150 KG CO/D.	Ash (1978) Frisbee (1983)
Electrolysis of CO to O ₂ +C	250 KG CO/Day	250	75	100 KG C/D. 150 KG O ₂ /D.	Ash (1978) Frisbee (1983)
Melting Ice for Water	Subsurface Ice	50	0.2	10 KG/Day	R. Williams, JSC (Pers. Comm.)
Extract Water from Clays	Clays, with 5% Water	130	5	10 KG/Day	C. Lin, JSC (Pers. Comm.)
Carbon Reduction of Iron From Oxides	Conc. Oxide 90% FE2O3	700	25	1000 KG/Day	R. Gettsch, Co Sch Mines (Pers. Comm.)
CAO Production from CA Carbonate	Conc. CaCO3	550	80	1000 KG/Day Port. Cement	R. Gettsch, Co Sch Mines (Pers. Comm.)
Glass Production	FSPAR, Silica, Clay	5450	23	1000 KG/Day Glass	M. H. McDonald Corning Ind. (Pers. Comm.)
Water Extraction from Carb. Chondrite	Unproc. Typ II Carb. Chond.	150	5.5	10 KG/Day	C. Lin, JSC (Pers. Comm.)
Electrolysis and Lique- faction of O ₂ , H ₂	10 KG Water/ Day	120	25	10 KG/Day (O ₂ & H ₂ , Liq.)	C. Lin, JSC (Pers. Comm.)

* Power requirements are based on conventional technology. Recent advances in use of microwave heating (Meek et al, 1978) may allow significant reduction in the power and mass of thermal power supply systems. JPL technology research is substantially reducing the mass and power requirements for CO₂ reduction and H₂ and O₂ liquefaction (E. Lawton, JPL, communication).

Extraction from Atmosphere

CO₂ can be concentrated from the atmosphere by compression. The CO₂ can be reduced electrolytically to CO and O₂. Ash (1978) proposed such a process as a source of rocket propellant. CO₂ can be reduced further to O₂ and elemental carbon. This requires significant quantities of electrical power. It is possible to condense water from the atmosphere; however, the abundance is so small that large systems will be required for extraction of significant quantities, making water extraction from ice or possibly clay minerals more practical.

Extraction from Ice

Water can be obtained from ice or permafrost by melting. A typical soil/ice permafrost may contain 25 - 35 percent water. As drilling through ice or permafrost may be difficult, it is recommended that ice be melted in the subsurface and pumped to the surface. Only low grade thermal energy is required.

Extraction from Clay Minerals and Martian Dust

If hydrated minerals are present in the regolith or in ancient sedimentary deposits, water may be extracted by simple heating. The amount of water in clays is probably less than 5 percent, and temperatures of 120 - 300 degrees centigrade may be necessary. Thermal energy may be available as a byproduct of other surface activities, such as the Mars base power system.

The Martian dust appears to be rich in iron oxides. It may be possible to extract metallic iron from these minerals, using electrolytically produced carbon as the reactant. Primary iron oxides in igneous rocks are an alternative source. Carbonates are believed to be present in the Martian regolith. If calcium carbonate is present, it may provide a source for the production of CaO to be used in portland cement for construction purposes. Phosphates (whitlockite) or feldspars may also be sources for CaO.

Utilization of Primary Rocks and Their Constituent Minerals

The major minerals of the igneous rocks of Mars are likely to be olivine, pyroxenes and feldspar. Silica (quartz) may be abundant locally. These rocks will find their first use as materials of construction, for example, as shielding materials or as aggregate in concrete. This will require mining, but not significant thermal or chemical processing. The abundance of feldspar, silica and clay minerals may provide ready materials for production of glass and ceramics, which could find use in construction and manufacturing. Data for a ceramics plant are included in Table 1.

Extraction of Propellant from Carbonaceous Chondrite (Phobos?)

Typical water contents of carbonaceous chondrites are : Type I, 20.8 percent; Type II, 13.4 percent; and Type III, 1.0 percent. Extraction of water can be achieved by heating to temperatures of 300 - 650 degrees centigrade. Production of cryogenic propellants would require electrolysis and liquification systems and significant electrical energy.

Better information on the nature and distribution of Mars resources is necessary in order to determine the accessibility of usable resources and in order to develop specific processes for their utilization. (This is unnecessary only for atmospheric CO₂). For those processes that involve chemical reactions with solid minerals of rocks and soil, mineralogical and chemical compositional data must be obtained by analysis of enough precision to identify the main minerals and determine their composition. This can be accomplished by in-situ or returned sample analysis of geologically characterized terrain on Mars. Similar information is needed for Phobos and Deimos. For those processes that require locating a specific resource, for example water ice, global orbital data may suffice, which will also allow the extension of detailed mineralogical and compositional data to other regions of the planet. This information will be significant in determining the rate of expansion of a human foothold on Mars, so should probably be obtained on precursor science missions, unless early manned missions are contemplated.

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